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The National Ignition Facility

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The National Ignition Facility

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ABSTRACT

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter-diameter target chamber and room for 100 diagnostics. NIF is the world's largest and most energetic laser experimental system, providing a scientific center to study inertial confinement fusion and matter at extreme energy densities and pressures. NIF's energetic laser beams will compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions. Other NIF experiments will study physical processes at temperatures approaching 10^8 K and 10^{11} bar; conditions that exist naturally only in the interior of stars and planets. NIF has completed the first phases of its laser commissioning program. The first four beams of NIF have generated 106 kilojoules in 23-ns pulses of infrared light and over 16 kJ in 3.5-ns pulses at the third harmonic (351 nm). NIF's target experimental systems are being commissioned and experiments have begun. This paper provides a detailed look the NIF laser systems, laser and optical performance, and results from recent laser commissioning shots. We follow this with a discussion of NIF's high-energy-density and inertial fusion experimental capabilities, the first experiments on NIF, and plans for future capabilities of this unique facility.

Keywords: High Energy Density Physics, Inertial Confinement Fusion, Laboratory Astrophysics, Solid State Lasers

1. INTRODUCTION

The National Ignition Facility (NIF), under construction at the Lawrence Livermore National Laboratory (LLNL) for the U.S. Department of Energy and National Nuclear Security Administration (NNSA), will be a scientific center for the study of inertial confinement fusion and the physics of extreme energy densities and pressures. Construction of the building that houses the laser system was completed in September 2001, and the installation of all 192 ultra-clean and precision aligned beampath enclosures was completed in September 2003. In late 2002, NIF began activating its first four laser beamlines. By July 2003, NIF had delivered world-record single-laser energy performance in primary (1.06 micron), second, and third harmonic wavelengths. When completed in 2008, NIF will provide up to 192 energetic laser beams to compress deuterium-tritium fusion targets to conditions in which they will ignite and burn, liberating more energy than is required from the laser to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions.¹⁻⁶

Detailed descriptions of NIF's laser architecture and the performance of the laser system have been presented recently.⁷⁻²⁴ Among the many challenges in designing and building NIF has been the design, engineering, construction, and commissioning of what is arguably the largest precision optical instrument ever built. Optics research, and laser science and engineering have taken place at NIF on a scale never before attempted. The optics and optical systems for NIF are the result of over thirty years of laser and optical materials research and development at national laboratories and in private industry throughout the world. On NIF there are more than 7500 large optics of 40 cm or greater transverse size including laser amplifier glass slabs, lenses, mirrors, polarizers, and crystals. An additional 26,000 smaller optical components are used in NIF. The total area of precision optical surfaces in NIF is nearly 4,000 square meters.⁶

NIF's laser systems are precisely aligned to better than 250 microns and point accuracy on NIF laser beams is 50 microradians. This precision placement had to be achieved over laser beam path lengths of 350 meters. In addition, NIF's beam-path is required to be extremely clean to ensure that laser optics remain free of dust particles. Special robotic transport and handling systems are used for all of NIF's modular optical components, which are assembled into large phone-booth sized line-replaceable units or LRUs.



Fig. 1. The National Ignition Facility at Lawrence Livermore National Laboratory.

We have now installed the optics and mechanical utilities required to activate 4 of NIF's energetic laser beams. Over the past year we have carefully studied the performance of these laser beams and we have carried out over 180 system shots. In addition, approximately 30% of the 7,500 meter-scale optics required for NIF have been completed as of the end of November 2003. These optics have been fabricated to NIF's specifications utilizing deterministic processes that were developed as a result of our multi-year research program. After a brief description of NIF's laser systems we will present some quantitative results on laser performance. In addition to the laser system, the first diagnostic systems to be used for both laser performance measurements and physics experiments have been installed and commissioned. These include static x-ray imaging, gated and streaked x-ray detectors mounted on the NIF target chamber, and a full-aperture backscatter diagnostic that images scattered light through the final optical beampath of the first four beams. With this initial suite of diagnostics, NIF experimenters have completed the first studies related to laser-plasma interactions applied to ignition hohlraum energetics and hydrodynamics.²⁵

2. A DESCRIPTION OF NIF

The NIF laser system is shown schematically in Figure 2. NIF consists of a number of sub-systems including amplifier power conditioning modules, the injection laser system consisting of the master oscillator and preamplifier modules, the main laser system along with its optical components, the switchyards, and the 10-meter target chamber and its target and diagnostic experimental systems. The entire laser system, switchyards, and target area is housed in an environmentally controlled building. An integrated computer control system is located in the core of the facility to monitor, align, and operate the more than 60,000 control points required for NIF's operation.²⁶ A large cleanroom facility, the Optics Assembly Building is located at one end of NIF for assembling and installing the precision optical and opto-mechanical components that make up the NIF laser system. On the opposite end of the facility the Diagnostics Building houses experimenters, experimenter data acquisition systems, and target preparation and storage areas.

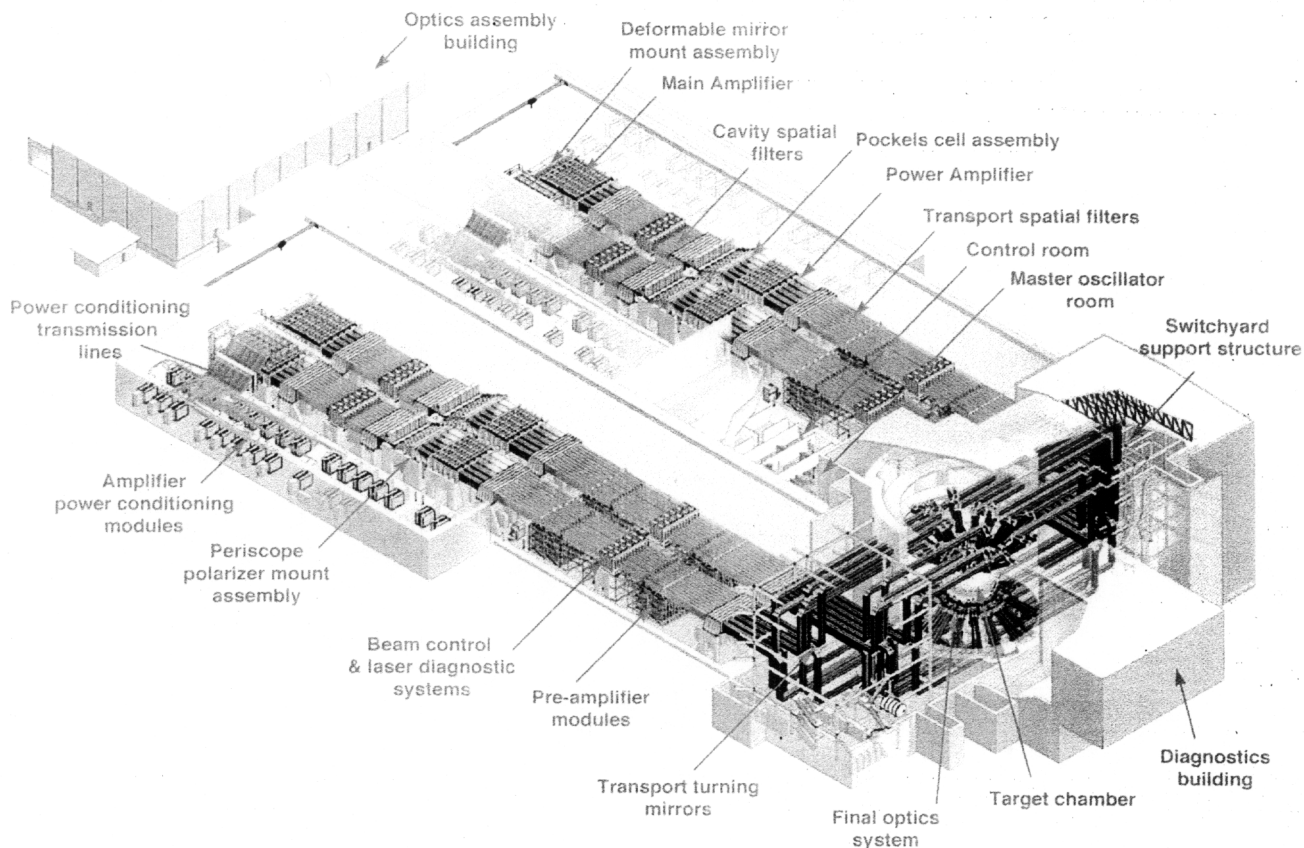


Fig. 2. Schematic view of the National Ignition Facility showing the main elements of the laser system. The 10-meter diameter target chamber sets the scale for the facility.

NIF's laser system is comprised of 192 high-power laser beams. For inertial fusion studies these laser beams will produce 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of laser energy in the near-ultraviolet (351 nanometer wavelength). This is approximately 60 times the energy available in the Nova laser, which was operated at LLNL between 1983 and 1999 and Omega Laser at the University of Rochester's Laboratory for Laser Energetics.

Figure 3 schematically shows one of the 192 laser beams, detailing the line-replaceable units that are used along the beam path. A NIF laser beam begins with a nanojoule energy laser pulse from the master oscillator and a diode-pumped fiber amplifier system that can provide a variety of pulse shapes suitable for a wide range of experiments, from complex high contrast pulses for ICF implosions to high-energy extended pulses. The master oscillator pulse is shaped in time and then transported to preamplifier modules (PAMs) for amplification and beam shaping. Each PAM first amplifies the pulse by a factor of one million (to about one millijoule) and then boosts the pulse once again by a factor of 20,000, this time to a maximum of 10 joules, by passing the beam four times through a flashlamp-pumped amplifier. There are a total of 48 PAMs on NIF, each feeding a "quad" of four laser beams. Figure 4 shows a photograph of NIF's Master Oscillator Room and Figure 5 show a NIF PAM.

From the PAM the laser beam next enters the main laser system, which consists of two large amplifier units – the power amplifier, and the multi-pass or main amplifier. These amplifier systems are designed to efficiently amplify the input pulse from the PAM to the mission-required power and energy, maintaining the input beam's spatial, spectral, and temporal characteristics. The amplifiers, with 16 glass slabs per beam, are arranged with 11 slabs in the main amplifier section and five slabs in the power amplifier section (the power amplifier can

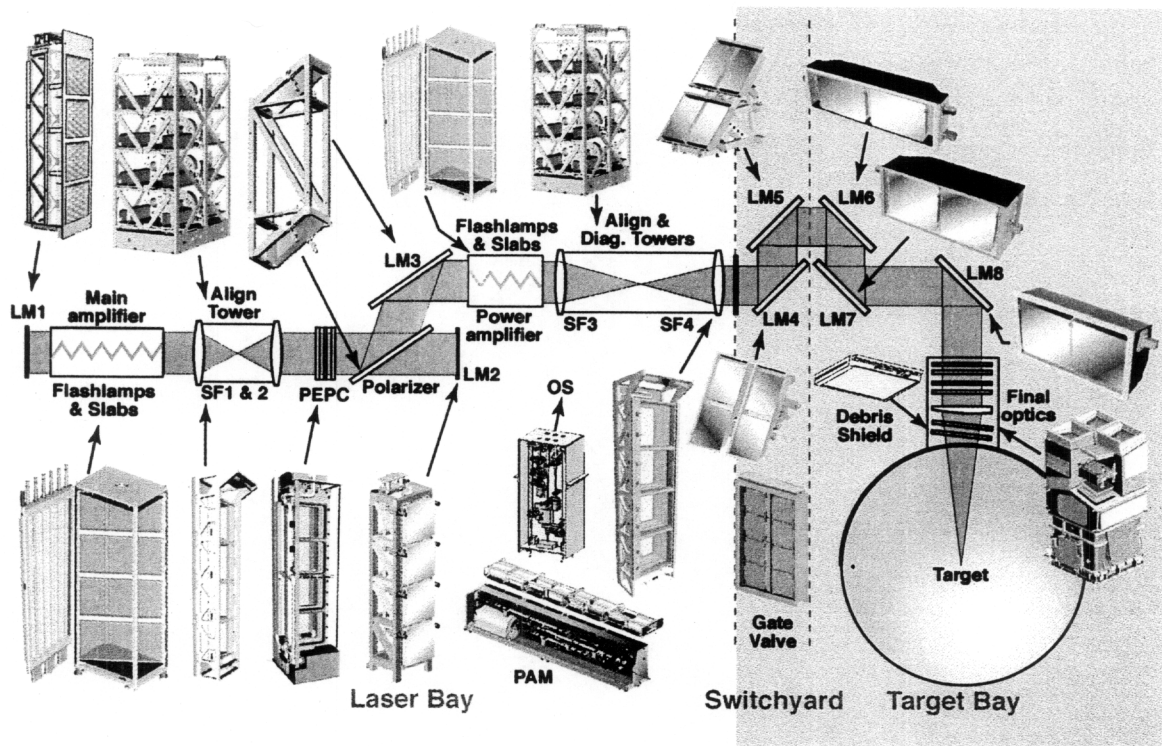


Fig. 3. Schematic representation of a NIF laser beam line showing the line-replaceable units used along the beam path.



Fig. 4. The NIF Master Oscillator Room (MOR) has been operating continuously since October 2001.



Fig. 5. NIF Preamplifier Module (PAM) undergoing testing in the Preamplifier Module Maintenance Area, which is located adjacent to the MOR in a dedicated Class 100 clean room facility.

actually accommodate 7 slabs per beam if necessary for future applications). Together, even though of relatively low gain, these amplifiers provide 99.9% of NIF's power and energy. The amplifiers use 42 kilogram slabs, measuring 46 cm x 81 cm x 3.4 cm, of neodymium-doped phosphate glass set vertically on edge at Brewster's angle to minimize reflective losses in the laser beam.²⁷⁻²⁸ The slabs are stacked four high and two wide to accommodate a "bundle" of eight laser beams (see Fig. 6).

The slabs are surrounded by vertical arrays of flashlamps, measuring 180 cm in length. A total of 7680 flashlamps and 3072 glass slabs are required for NIF's 192 laser beams. Each flashlamp is driven by 30,000 joules of electrical energy from the Power Conditioning System (PCS), which consists of the highest energy array (about 400 megajoules) of electrical capacitors ever assembled.²⁹ The intense white light from the flashlamps excites the neodymium in the laser slabs to provide optical gain at the primary 1.06 micron infrared wavelength of the laser. Some of the energy stored in the neodymium is released when the laser beam passes through the slab. Advances in glass amplifier technology allow NIF to operate with less than twice the number of flashlamps than Nova even though the laser system will produce 60 times more output energy. The flashlamps are cooled between shots, along with the amplifier slabs, using nitrogen gas so that NIF can be fired once every four hours. Figure 6 shows how flashlamps and laser glass are assembled and installed into the NIF beampath.

A key component in the laser chain is an optical switch called a plasma-electrode Pockels cell (PEPC), which allows the beam to pass four times through the main amplifier cavity.³⁰ This device uses electrically induced changes in the refractive index of an electro-optic crystal, made of potassium dihydrogen phosphate (KDP). When combined with a polarizer, the PEPC allows light to pass through or reflect off the polarizer. The PEPC will essentially trap the laser light between two mirrors as it makes four one-way passes through the main amplifier system before being switched out to continue its way to the target chamber. The PEPC consists of thin KDP plates sandwiched between two gas-discharge plasmas that, although having no effect on the laser beam passing through the cell, serve as conducting electrodes, allowing the entire surface of the thin crystal plate to charge electrically in about 100 nanoseconds so the entire beam can be switched efficiently. Figure 7 shows a four-cell PEPC (optical switch) in operation that will be oriented vertically in a single unit when inserted into NIF's beampath.

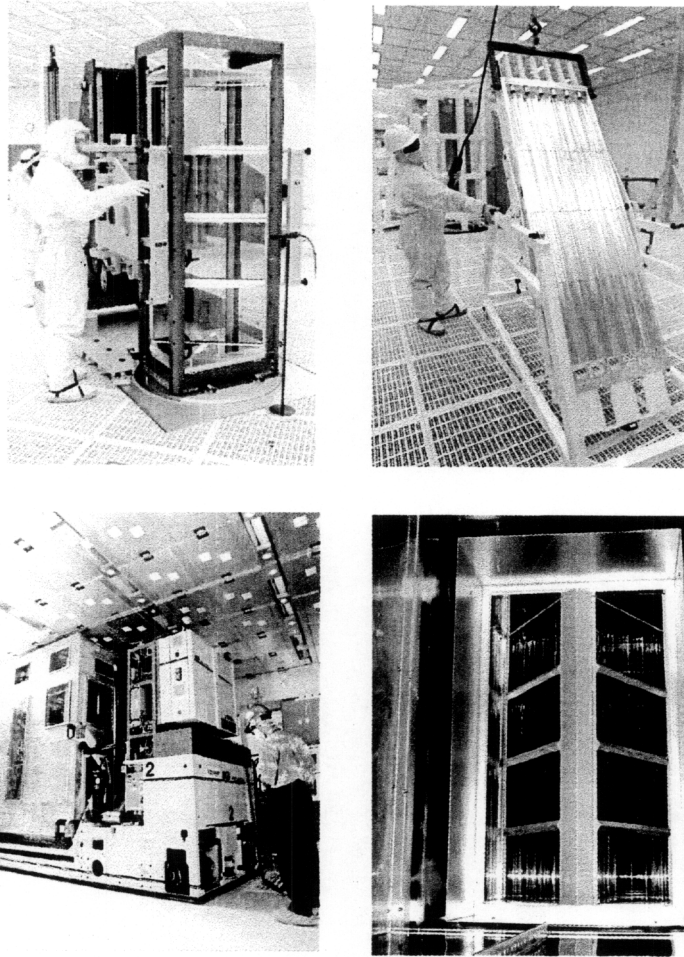


Fig. 6. Laser glass slab and flashlamp cassettes, shown in the top left and right photographs are examples of NIF LRUs. The LRUs are inserted into the laser beampath using autonomous guided vehicles carrying portable clean canisters, shown in the bottom left photograph. One section of the assembled amplifier system is shown in the bottom right photograph.

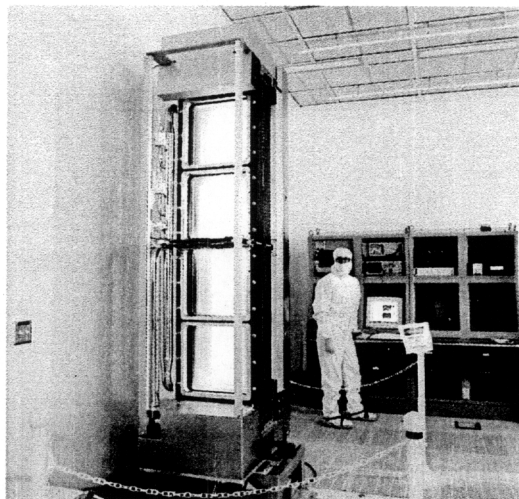


Fig. 7. Plasma Electrode Pockels Cell LRU undergoing testing in the OAB.

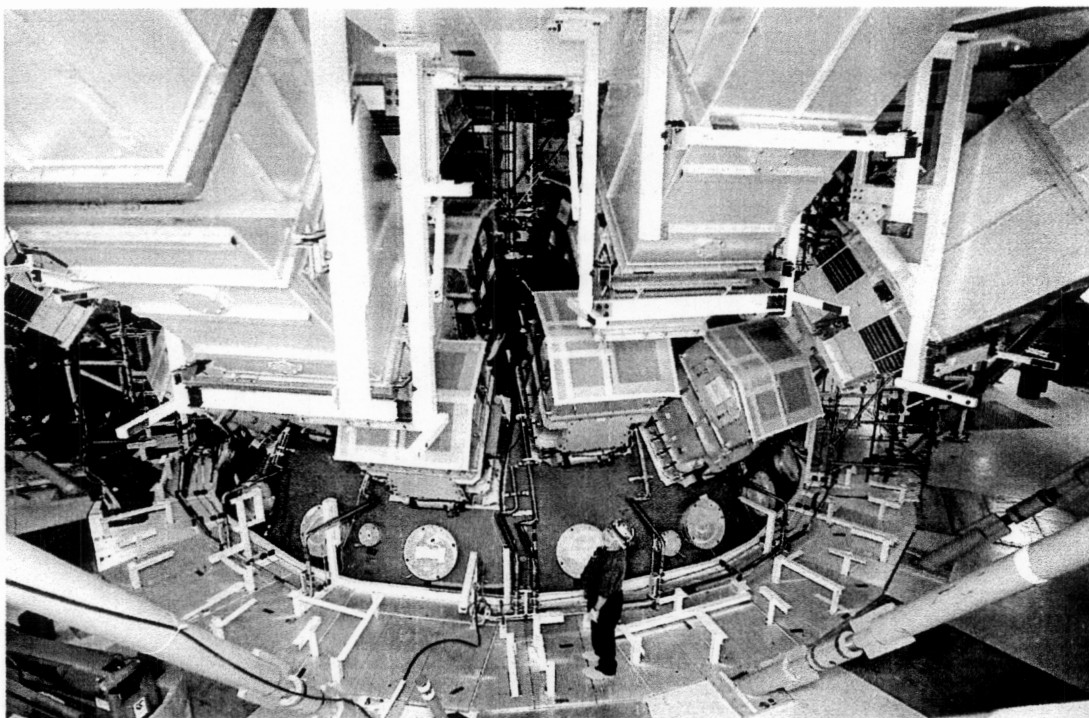


Fig. 8. Target chamber upper hemisphere showing 24 quads of beam tubes installed.

All major laser components are assembled in clean, pre-aligned modules called line-replaceable units or LRUs, shown in Figure 3. These LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filter assemblies that are robotically installed into NIF's beampath infrastructure, while maintaining the high level of cleanliness required for proper laser operation. Autonomous guided vehicles carrying portable clean rooms position themselves underneath NIF's beampath enclosures and robotically insert LRUs into the beampath. The installation, integration, and commissioning of the beampath infrastructure at the required cleanliness levels has been successfully accomplished for the more than 120 LRUs required for NIF's first four laser beam lines.

The NIF target chamber and final focusing system is designed with maximum flexibility for experimental users and includes 120 diagnostic instrumentation and target insertion ports. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs the laser beams into two cones in the upper and lower hemispheres of the target chamber. This configuration is optimized for illuminating the fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to implode the capsule. NIF can also be configured into a more symmetrical "direct drive" arrangement of beams.³¹ Figure 8 shows a recent photograph of the upper half of the target chamber. Each laser entry port allows a quad of laser beams to be focused to the center of the target chamber through a final optics assembly (FOA). The FOA is a precision optical assembly containing optics to provide a variety of beam profiles on target, KDP and deuterated KDP plates to convert the infrared laser light into the ultraviolet, the final focus lens, debris shields and vacuum gate valve for each beam.

3. NIF EARLY LIGHT

NIF construction began in May 1997 and nearly all 192 beampath enclosures are now in place and ready for optics installation. Figure 9 shows the beampath installed in Laser Bay 2. In October 2001 the first laser light from NIF's master oscillator was generated in the master oscillator room located in the central core of the NIF building. This master oscillator has demonstrated the required pulse shaping stability and accuracy for high contrast ignition pulses and other types of laser pulses that are of interest to NIF experimenters. In June 2002 the first preamplifier module was installed in the Laser Bay and routinely amplifies master oscillator pulses to the joule level.

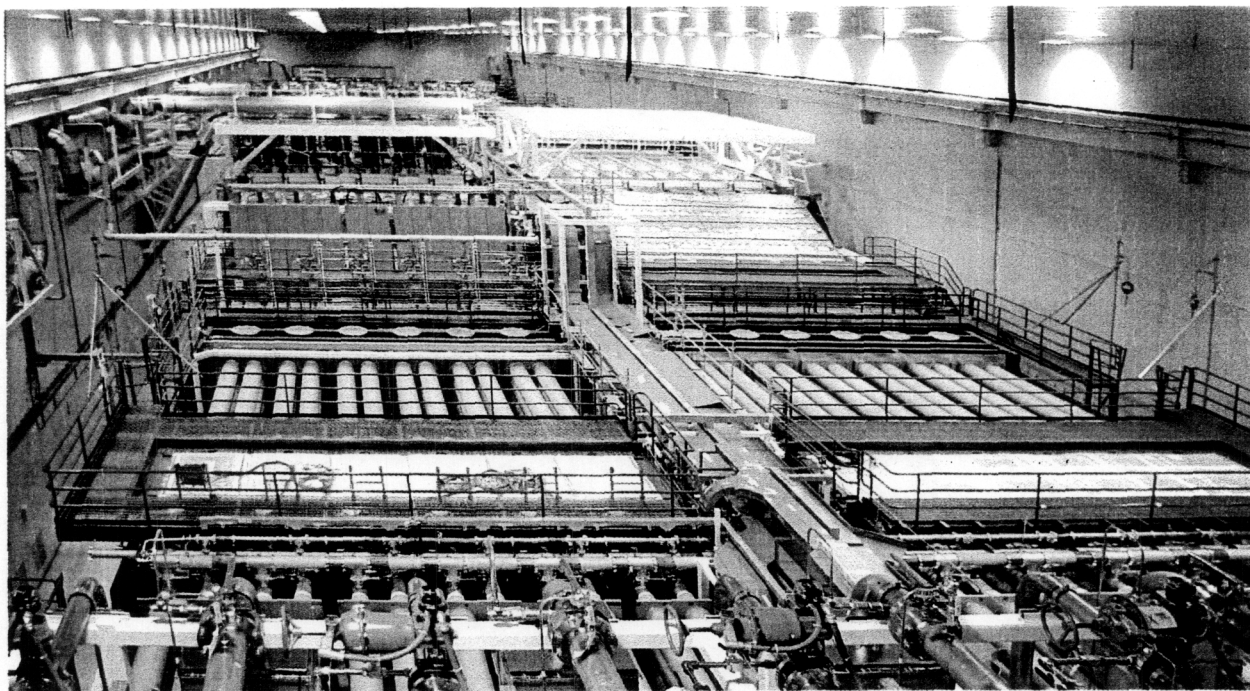


Fig. 9. The completed beampath for 96 laser beams in Laser Bay 2.

First high energy 3ω laser light to the center of NIF's target chamber was achieved in January 2003 with approximately 1 kilojoule (kJ) of laser energy focused onto a simple foil target. The energetic x-rays emitted from this target were measured with an x-ray pinhole imaging system called the Static X-ray Imager (SXI) mounted on the target chamber. In April 2003 10.6 kJ of 3ω light was produced in four beams and directed to a target in the target chamber. Recently we have delivered 16 kJ of 3ω light in four beams to the target chamber for experiments.²⁵

A separate target chamber, known as the Precision Diagnostic System (PDS) is used to fully characterize NIF's 1ω , 2ω , and 3ω laser beam energy, power, and wavefront to validate and enhance computer models that predict laser performance. Any one of the four NIF beams can be directed into the PDS using a robotic mirror and transport system. Figure 10 shows examples of high-energy 2ω and 3ω beams imaged in the near field using the PDS.

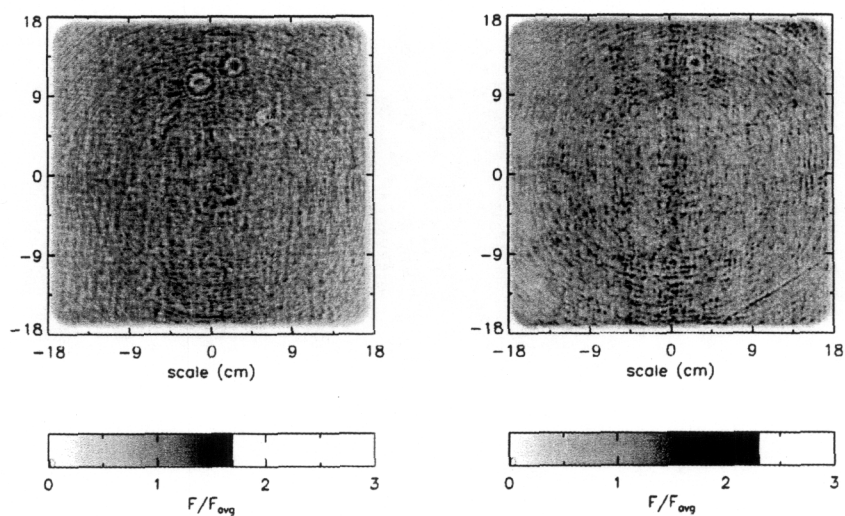


Fig. 10. Near field image of an 11.4 kJ 2ω and 10.4 kJ 3ω NIF beams showing excellent contrast uniformity, exceeding NIF's requirements.

At this time NIF's highest 3ω single laser beam energy is 10.4 kJ, equivalent to 2 MJ for a fully activated NIF, exceeding the NIF energy point design of 1.8 MJ. This energy was achieved with 13.65 kJ 1ω drive in a 3.5 ns pulse. We have also conducted a series of shots generating green or 2ω laser light with single beam energy up to 11.4 kJ in a 5 ns square pulse. This is equivalent to nearly 2.2 MJ on target for 192 beams. In July 2003, 26.5 kJ of 1ω light per beam was produced. This energy is 30% greater than the drive energy required for NIF. NIF has now demonstrated the highest energy 1ω , 2ω , and 3ω beamlines in the world. High power campaigns have also been completed with drive power reaching 7 terawatts or about 5 gigawatts/cm². Figure 11 details energy and power achieved on a number of 1ω shots conducted through July 2003.

Beam-to-beam synchronization has been measured and adjusted to better than 6 picoseconds, which corresponds to approximately 1 part in 150,000 of the total beampath in NIF. Figure 12 shows this measurement using an x-ray streak camera diagnostic demonstrating NIF's timing performance. Complex shaped ignition pulses as well as ramped and flat-in-time pulses with multi-kJ energies and pulse lengths up to 25 ns have also been demonstrated.

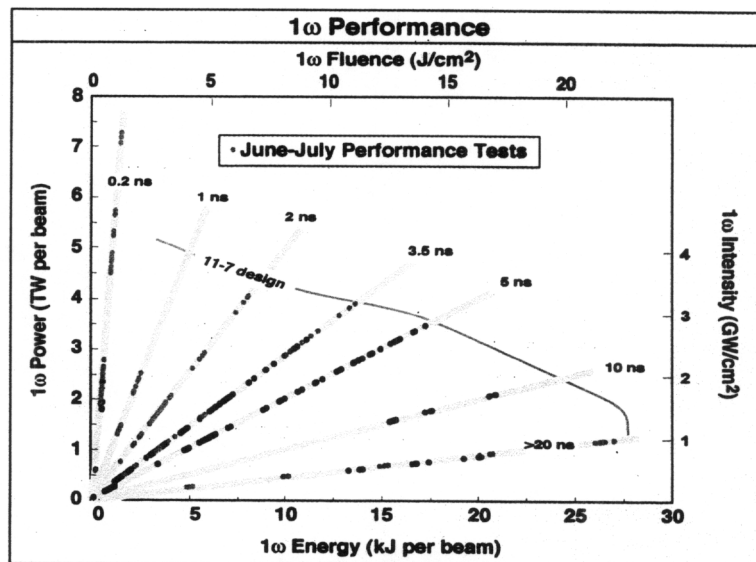


Fig. 11. 1ω energy vs. power is plotted for a number of NIF performance shots. The plot also indicates the level where energy and power is limited by the available number of glass slabs in the main amplifier (11 slabs) and the power amplifier (7 slabs).

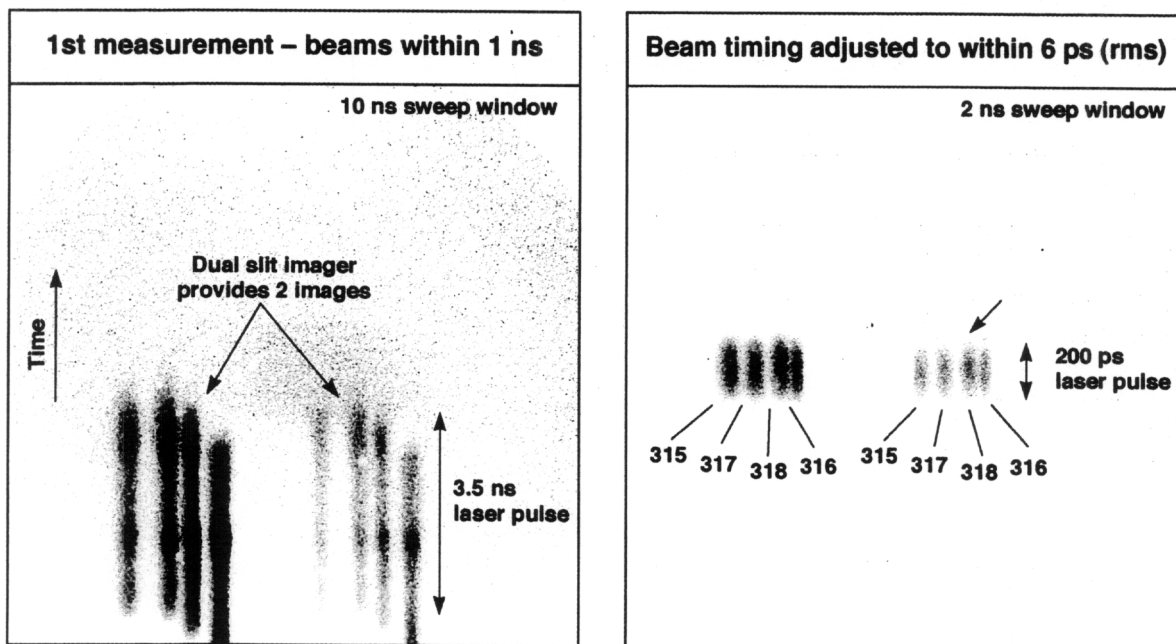


Fig. 12. Streaked x-ray images showing the beam-to-beam timing for a quad of four laser beams. Each image shows x-rays emitted from a target illuminated by the quad of beams and imaged through two different thickness filters.

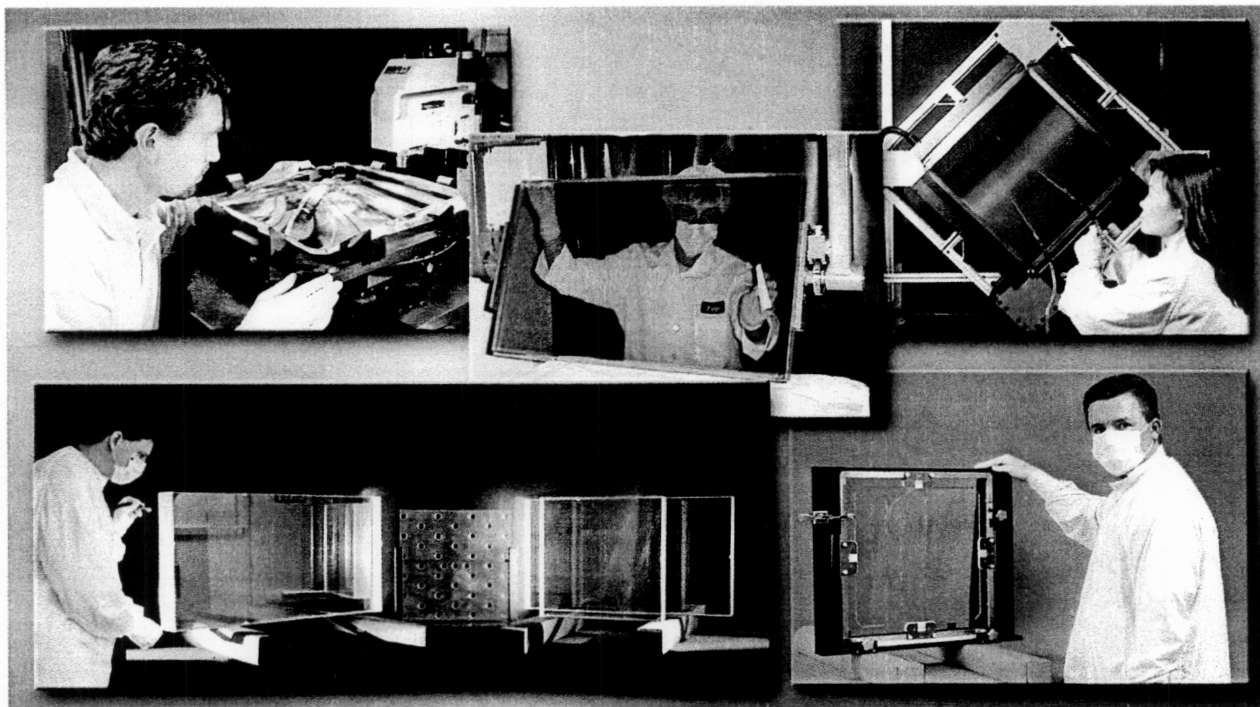


Fig. 13. Examples of large optics used on NIF. Clockwise from upper left: fused silica wedged focus lens, neodymium-doped phosphate laser glass slab, fused silica beam sampling grating, KDP frequency conversion crystal, and BK7 mirrors and polarizers.

4. NIF OPTICS

Optics production and finishing has been a major area of research over the past three years with an emphasis on making the finishing process more deterministic, reducing the iterative nature of traditional final figuring, and the optic preparation time (grinding and shaping) to prepare the optic for final figuring.³²⁻³⁹ NIF vendors are now producing substantial numbers of optics that meet our requirements. A significant investment has been made in vendor facilitization programs, resulting in the installation of equipment based on new technology to meet the production capacity and metrology requirements for NIF.⁶ Currently NIF's finishing vendors have finished approximately 30% of the optics required for NIF's 192 laser beams. NIF meter-scale optics suitable for high fluence operation with the required wavefront specification are being manufactured at a production rate of over 100 optics per month and we are following a schedule for completing production for all the necessary optics for 192 beam lines by 2007. Figure 13 shows some examples of the large aperture optics being used in NIF.

5. EXPANDING SCIENTIFIC HORIZONS USING THE NATIONAL IGNITION FACILITY

The National Ignition Facility extends the high-energy-density (HED) experimental regimes of current and planned high-energy laser and pulsed-power facilities by a significant amount. Figure 14 displays one measure of NIF's physics reach for temperature and density of materials. NIF will be able to reach conditions of matter that exist in the sun and larger stars, giant planets such as Jupiter, and brown dwarfs that are thought to make up a significant amount of the matter in our universe. With the planned addition of a one-picosecond pulse beam, NIF will be able to reach extreme states of matter more typically associated with nuclear and high-energy-physics accelerator experiments. In this way, NIF can explore the physics of matter at temperatures approaching those that existed in the very early universe.

NIF can drive materials to tens of gigabars for pulse lengths of tens of nanoseconds. NIF is capable of providing a range of pulse lengths that under certain configurations can be hundreds of nanoseconds. The ability to deliver extended high-energy drive allows experimental measurements of equation of state (EOS), materials at high pressures, hydrodynamics, and radiation transport that have not been possible in prior HED facilities. NIF opens up new fields of study, for example in the area of warm dense matter (WDM) – approximately solid density matter at temperatures in the few eV to tens of eV range.⁴¹ Currently there is no theory that adequately describes WDM. NIF's high-energy laser beams can be tailored for driving relatively large uniform volumes. NIF beams can also be used to provide high x-ray fluences for high signal-to-

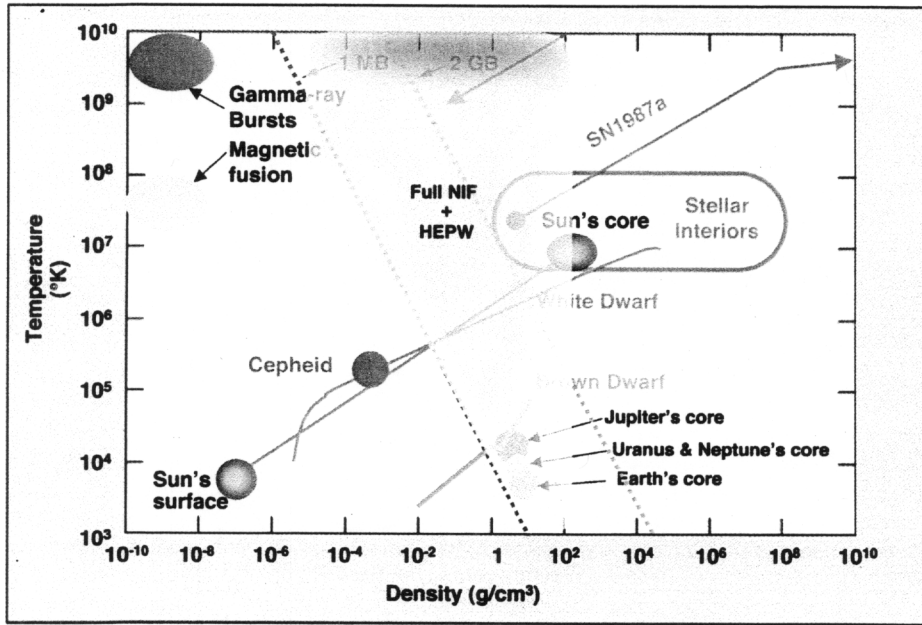


Fig. 14. High-energy density is a prevailing condition in astrophysics. This figure shows how NIF can reach conditions of extreme temperature over a range of material densities that are relevant to a variety of astrophysical phenomena. NIF, with high-energy petawatt (HEPW) short-pulse laser capability, can reach conditions approaching those in existence near the time of the Big Bang.⁴⁰

noise radiography of dense matter. High-energy picosecond laser pulses can provide extremely high brightness and high-energy x-ray backlighter sources for radiographing WDM to fully resolve hydrodynamic features and materials states.^{24,42}

Even with the first four beams of NIF, materials can be subjected to tens to one hundred megabars of pressure. Initial EOS experiments with the first four NIF beams are planned in the coming year that have a goal of exceeding 25 Mbar in aluminum⁴³ in a steady and uniform pressure wave. Isochoric heating with ignition neutrons or high energy petawatt laser-generated ion beams when they become available in the coming decade provides an additional capability for heating materials off the Hugoniot.

6. LABORATORY ASTROPHYSICS

The National Academy of Sciences in the United States has recently recognized the exciting scientific frontiers becoming available at the next generation of high-energy-density experimental facilities.^{44,45} Laboratory-based astrophysics experiments, simulating extreme physics phenomena heretofore inaccessible, are now becoming feasible for the first time. For example, supernovae explosion mechanisms remain uncertain. Recent planar and spherical RT experiments on Nova and Omega showed that instabilities produced in these systems can be quantitatively studied. Figure 15 compares experiments and simulations showing qualitative similarities in their behavior. In fact, a variety of scaled experiments using NIF are possible, studying not only large-scale mixing phenomena associated with supernovae, but also radiatively driven shocks that can lead to 2D jets and 3D spherical shocks observed in astrophysics. Figure 16 displays an astronomical event with a laboratory-scaled experiment. Researchers are assessing NIF's potential for simulating exotic astrophysical systems such as the extended RT systems in the Eagle nebula, immense astrophysical radiative magnetohydrodynamic jets,⁴⁶ and even possibly the incredible physical conditions that exist only near the surface of a neutron star.⁴⁷ Figure 17 displays examples of these phenomena and associated laser-driven analog experiments. Note the extreme scaling in both time and space between laser experiments and the astrophysical objects in these figures. NIF will provide the capability to study larger-volume targets for longer times and high-fluence. High-energy time-resolved x-ray data will help to validate hydrodynamic models that can be scaled to stellar dimensions and times.

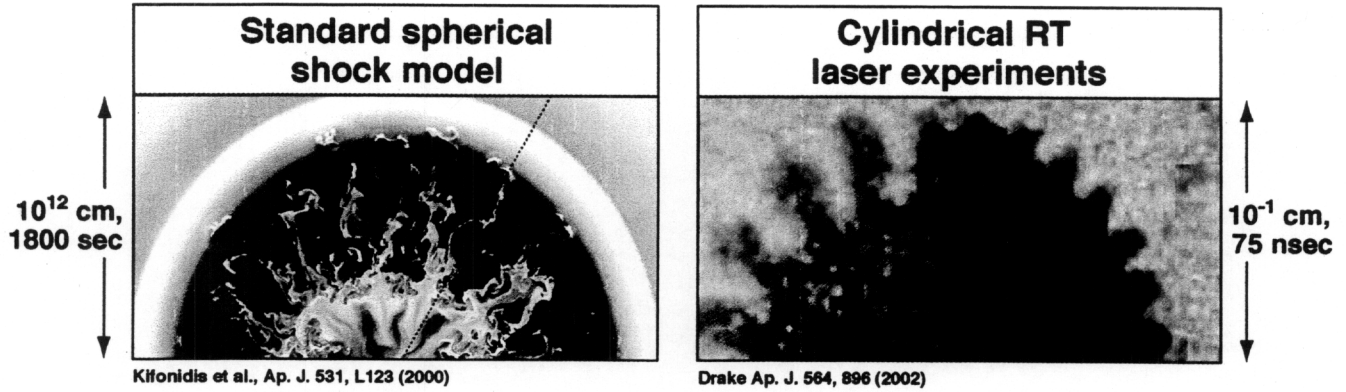


Fig. 15. Comparison of instabilities generated in a spherical shock model of supernovae, left, with RT experiments conducted using scaled targets driving by lasers. The image on the right show RT growth between 55 and 75 nsec on a scale of about 0.1 cm, that are qualitatively similar to the supernova model.

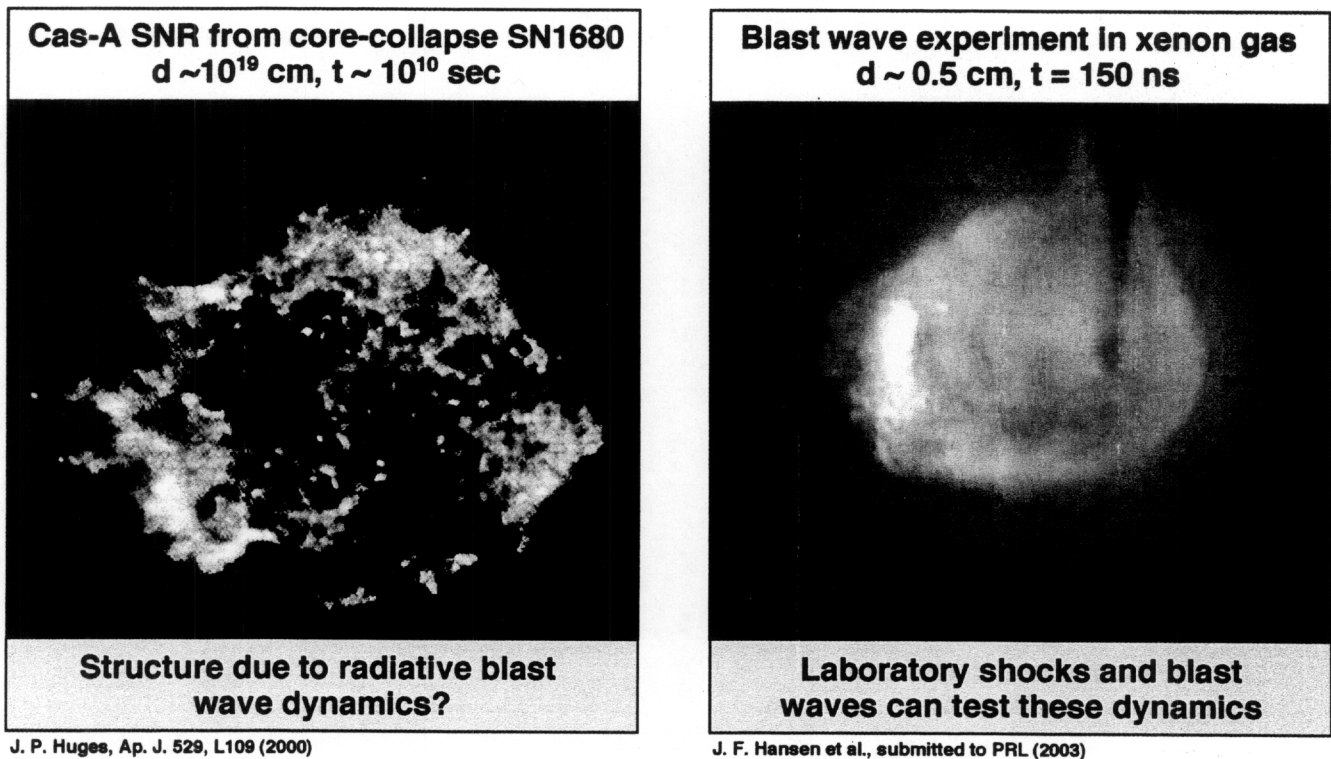


Fig. 16. Radiative shocks such as supernova blast waves can be simulated using scaled gas-filled targets illuminated by energetic laser beams. The photograph on the left is a Supernova Remnant (SNR) in Cassiopeia-A, which occurred in the year 1680. In the image on the right, a beam incident from the left has initiated an expanding radiatively driven shock that is outrunning the material expansion from the target itself. This is seen as the faint glow surrounding the brighter inner sphere.

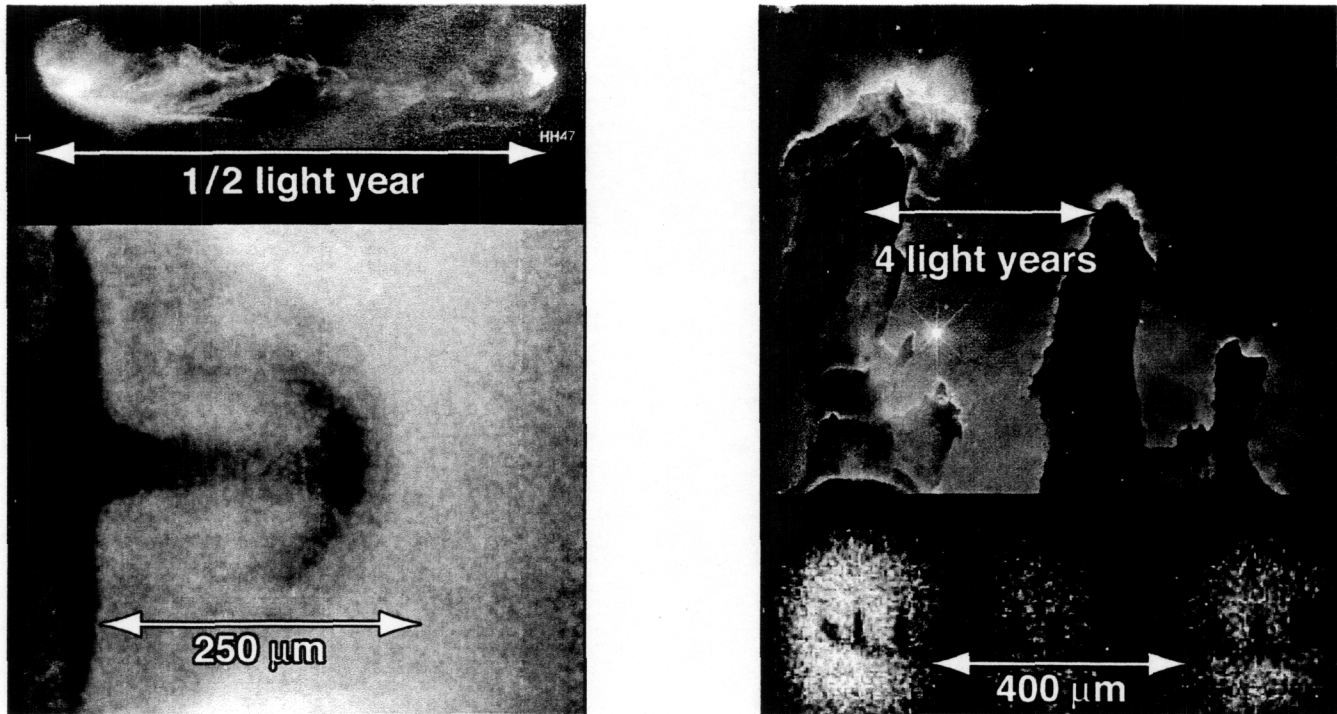


Fig. 17. Additional examples of scaled astrophysical phenomena that can be simulated using lasers. On the left is an astrophysical jet compared with a laser-generated jet using the Omega laser. On the right the striking structures in the Eagle nebula are compared with similar RT structures generated using the Nova laser.

7. IGNITION ON NIF

One of the key missions of NIF is to generate and study thermonuclear ignition and energy gain using the 192 lasers of NIF to compress and heat small capsules containing a mixture of the heavy hydrogen isotopes of deuterium and tritium. Figure 18 diagrams how inertial confinement fusion (ICF) is carried out using lasers. Carefully prepared ignition capsules containing the fusion fuel in a thin, very smooth frozen layer surrounding a pressurized DT gas volume are contained in precisely formed plastic or copper-doped beryllium shells. The capsule is suspended in a hollow gold cylinder with laser entrance windows on each end. This structure is called a hohlraum. Carefully focused and temporally-shaped laser beams are directed into the hohlraum through the ends and deliver their energy to the inside walls, generating intense x-rays that uniformly illuminate the capsule. The x-rays ablate the outer surface of the capsule very rapidly. The reaction force from the ablation drives the fusion fuel inward, compressing and heating it to the conditions necessary for thermonuclear fusion reactions to self-initiate. Under the proper conditions, the thermonuclear reactions will propagate outward in a fusion burn, consuming all of the fuel and liberating more energy than was used to drive the target. This type of ICF target is also called an indirect-drive target because the laser beams are not incident directly on the fusion capsule. Indirect-drive targets are advantageous because they tend to smooth out imperfections in the laser drive associated with laser energy and uniformity.

In NIF a “point design” ignition hohlraum and capsule has been developed using increasingly sophisticated 3D computer calculations. The most recent calculations, shown in Figure 19, performed on LLNL’s ASCI supercomputer system indicates the production of about 20 megajoules of fusion yield in the form of energetic 14-MeV neutrons, x-rays, and gamma rays for about 2 megajoules of UV light delivered from the 192 laser beams.

Prospects for ignition on NIF continue to improve.^{31,48} Designs supporting indirect-drive, or x-ray drive of ignition capsules in hohlraums are becoming more robust as better modeling capability, including full 3-dimensional modeling of capsules and hohlraums allows design trade-off studies to be rapidly performed and design spaces to be optimized. For example, optimization studies have improved plastic capsule performance by a factor of two while allowing ablator roughness to increase by a factor of two, easing fabrication requirements.

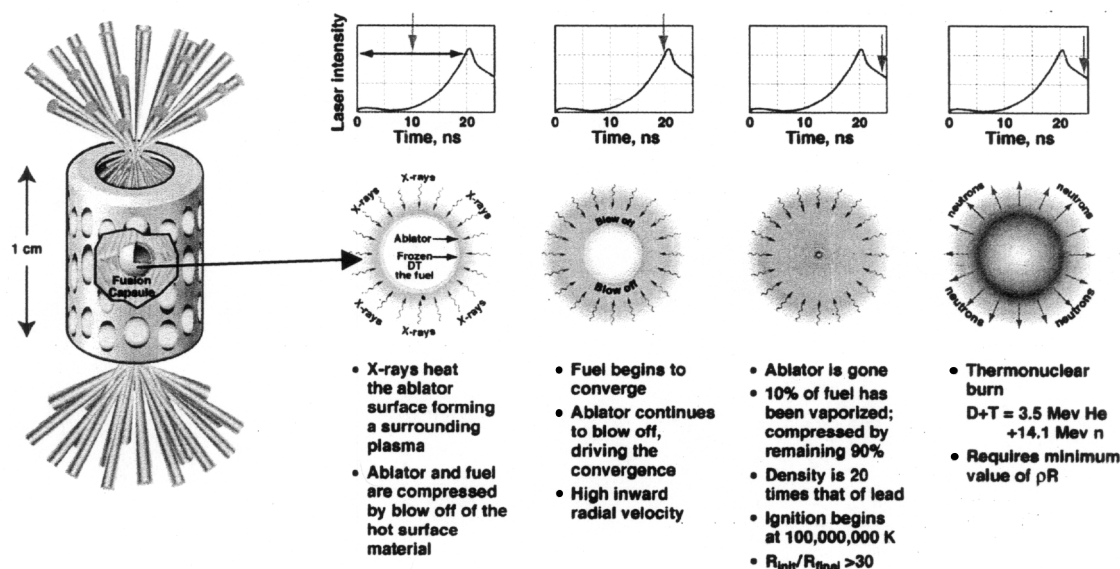
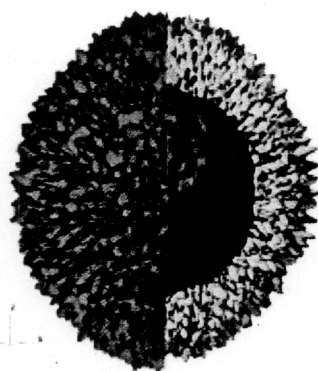
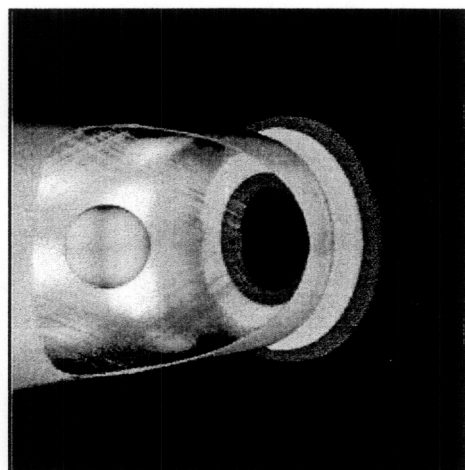


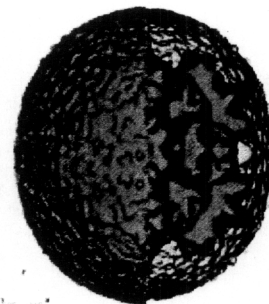
Fig. 18. A schematic representation of a NIF indirect-drive hohlraum target is shown on the left. NIF's 192 laser beams are grouped in 48 "quads" of four laser beams that are directed in opposite ends of the hohlraum to produce the x-ray drive. The time sequence on the right shows how the x-rays interact with the fusion capsule to create ignition and burn with energy gain.

New designs using beryllium with graded Cu dopant are particularly robust, with ablator roughnesses being relaxed by as much as a factor of 10-20 over previous designs and newly optimized polyimide designs. In addition, significant progress has been made in fabricating smooth plastic and beryllium/copper capsules that nearly meet these new design specifications.

Precision control of cryogenic D_2 ice smoothness using infrared heating in an isothermal hohlraum has now been demonstrated. Progress is also being made in developing cryogenic hohlraums with convection mitigation and thermal control. Diffusion filling of a capsule in a hohlraum has also been recently demonstrated and integration of infrared layering, thermal shimming, convection mitigation, and characterization in a D_2 test system is under way.⁴⁹



140 ps before
ignition time,
60 g/cc



Ignition time,
400 g/cc density
isosurface (not to
scale)

Fig. 19. Full 3-D calculation of capsule implosion showing ignition conditions predicted for a point-design NIF ignition target. This calculation used 12.8 million zones and 120 processors and produced a yield of 22 Megajoules. The figure at the left shows one half of the hohlraum with laser beams entering from the right. The figures at the center and right show two different views of the DT capsule as it is undergoing implosion.

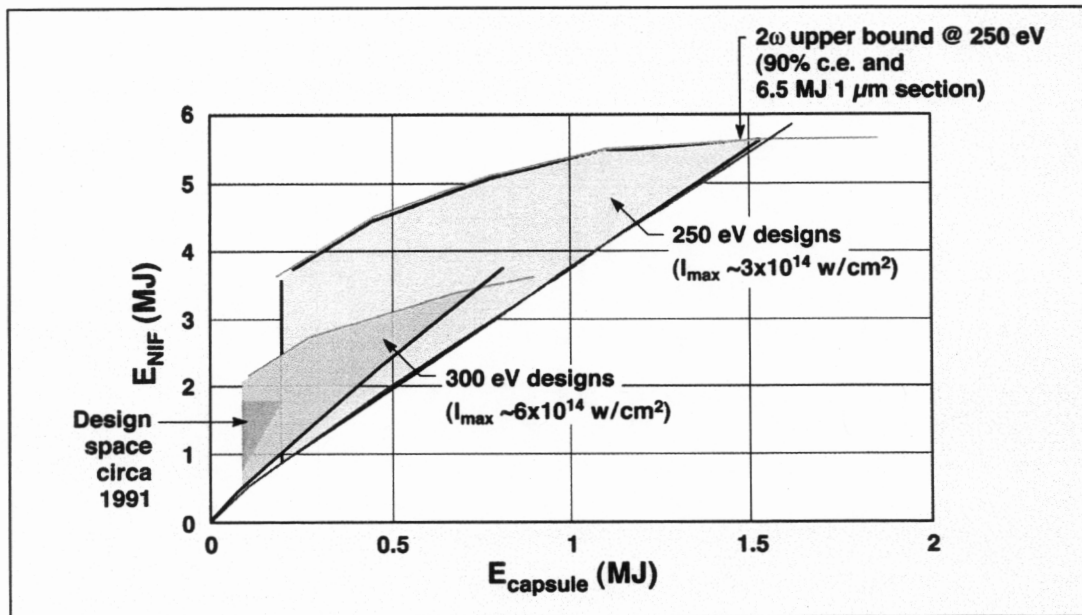


Fig. 20. Recent calculations of energy coupled to the capsule in the form of X rays converted from incident laser energy is shown in this figure. NIF's 1991 design space is shown in the lower left. The figure shows that the design space can be significantly increased for 2ω laser drive. Two extended regions show hohlraums driven to 300 eV and 250 eV, indicating that as much as 1.5 megajoules of x-ray drive energy may couple to a capsule at 250 eV temperature.

Hohlraums driven with green or 2ω laser light from NIF are also actively being studied.⁵⁰ Figure 20 shows recent calculations suggesting that as much as 1.5 MJ of energy may couple to a capsule at 250-eV drive temperature. However, physical data on 2ω laser plasma interactions is limited and more work is needed. NIF 2ω operation has been demonstrated and researchers are studying how to configure some of NIF's early beams for high-energy 2ω LPI studies.

Finally, fast ignition experiments using the Gekko Laser at the University of Osaka, Institute for Laser Engineering, and the Vulcan Laser at Rutherford Appleton Laboratory in the UK are providing tantalizing glimpses of possible low-energy symmetric heating combined with high-power asymmetric drive to induce hot-spot ignition conditions in cone-focused targets.^{51,52}

A "proof-of-principle" fast-ignition experiment at NIF is in the design phase. Laser physicists have determined how NIF's current injection laser, main amplifier, and beam transport system could be modified to allow up to 20 high-energy petawatt-class (HEPW) beams to be directed to target chamber center. Initial experiments are being designed to utilize a single kilojoule-class HEPW beam line with 1-30 picosecond pulse width to drive electron or proton cone-focused ignition experiments. Initial short-pulse capability on NIF is planned to be in place in the 2006 time frame.⁵³ Additional HEPW beams in a quad could be installed to provide multi-kilojoule capability.

5. NIF AS AN INTERNATIONAL SCIENCE CENTER

The first four beams of NIF have been available for laser performance studies and experimental for approximately one year. In that time over 200 full system shots have been carried out on NIF. In addition a sophisticated suite of experimental diagnostics has been fielded on the 10-meter diameter target chamber and are available for use. These include static and gated x-ray imaging and streak cameras, full-aperture back scatter system, and a laser interferometer system for measuring shock velocities. The first physics experiments are already being performed on NIF. Initial experiments are studying laser-plasma interactions that are important for understanding the propagation of laser beams and the delivery of energy into ignition hohlraums. Other experiments are studying hydrodynamics of materials undergoing laser-driven shocks. Figure 21 shows results from a recent experiment directing NIF's first four beams with 16 kJ of ultraviolet light into a gas-filled target. The x-ray images compare favorably with sophisticated calculations. In the coming year, we are planning experiments to study materials equations of state and the hydrodynamics of shocked materials.

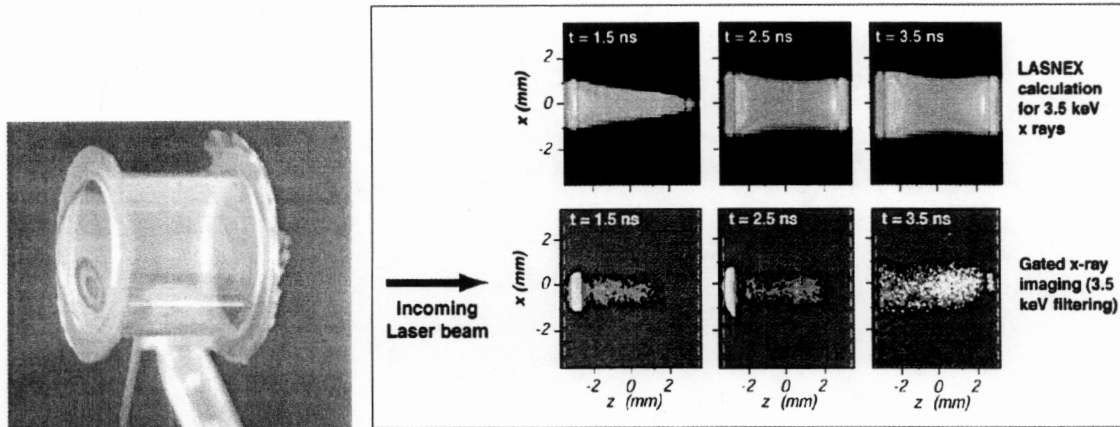


Fig. 21. Laser-plasma interaction experiments have been fielded on NIF using cm-scale CO_2 gas-filled targets, shown on the left. Results from the first physics experiments on NIF using these targets are shown on the right using a gated x-ray imaging diagnostic. This data can be compared with computer models that qualitatively agree with the data.

6. THE PATH FORWARD TO FULL NIF

Completion of all 192 laser beams is scheduled for September 2008. We have developed a plan for beam deployment that supports experiments with steadily increasing capability displayed in Figure 22. Currently NIF is configured with four beams. We are preparing to build out the rest of the laser system beginning in FY 2005. The increasing symmetry and energy available as the number of beams increases enables a variety of target configurations including planar targets, horizontal and vertical half-hohlraums (halfraums), and vertical hohlraums with 4- and 8-fold symmetry. After project completion, NIF is expected to ramp up to approximately 700 shots per year for a wide variety of experimental users as a national user facility. A recent shot campaign on NIF provided three target shots per day over a three-day period, giving us confidence in NIF's ability to meet the planned 700 shots per year when it is fully operational. We have also developed a plan for fielding facility diagnostics that is synchronized to the increasing capability NIF provides.

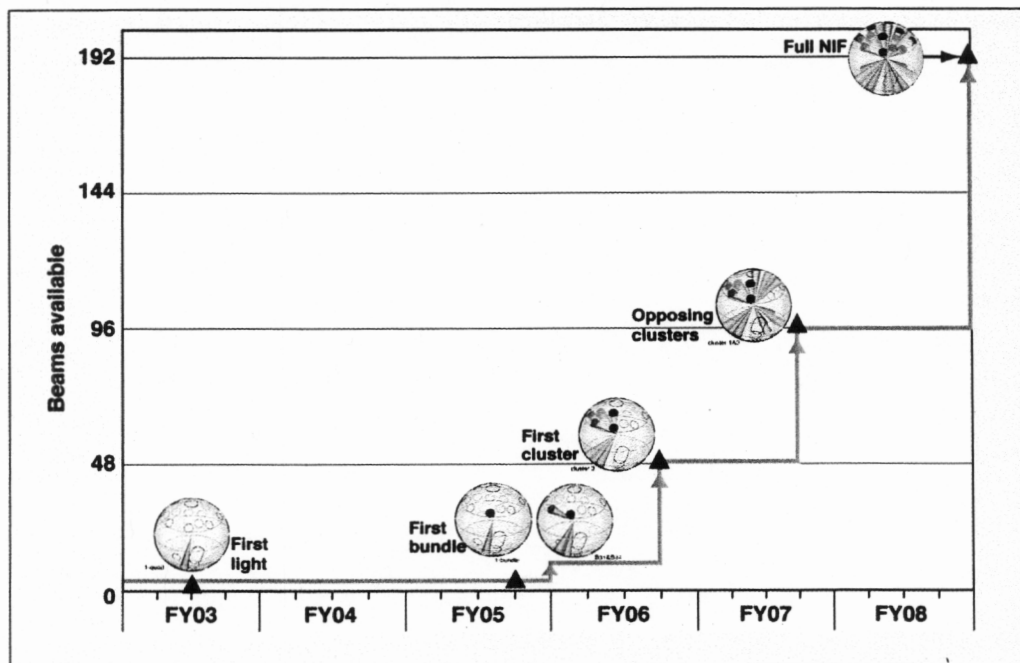


Fig. 22. As additional NIF laser beams are installed, increasing capability becomes available and experimenters can take advantage of beam symmetry and energy to perform increasingly sophisticated experiments. In addition, specialized diagnostics will become available in parallel with the build-out and commissioning of the laser system.

In addition to diagnostics, the NIF Program includes support for building and commissioning facility capabilities in diffractive optics (phase plates), cryogenic target systems, and target area operations. We are developing a non-ignition cryogenic target capability to be fielded around the time of first cluster.

As NIF matures, we fully expect the facility to evolve to include exciting new capabilities, some of which are mentioned briefly here. The NIF laser system and support buildings have been designed with maximum flexibility for future enhancements such as multi-wavelength operation and high-energy short-pulse operation. NIF is ready to deliver the next generation of HED and ICF experimental capability for the US and international scientific communities.⁵⁴

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